IDS#125951 (990.0505) Attorney Docket No. Greywall 29

APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

MEMS-BASED SPECTROPHOTOMETRIC SYSTEM

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"Express Mail" Mailing Label No.EV140154232US Date of Deposit 09/22/2003

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MEMS-BASED SPECTROPHOTOMETRIC SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

The subject matter of this application is related to that of U.S. Patent Application No. 10/153,294 filed on 05/22/2002 and entitled "Monolithic In-Plane Shutter Switch," the teachings of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to sensors and, more specifically, to optical gas detectors.

Description of the Related Art

Gas analyzers are used in environmental monitoring, industrial process control, geologic exploration, and medical, analytical, and military applications. For example, gases such as hydrogen sulfide and sulfur dioxide accompany natural gas and are often present in industrial environments. Since exposure to these gases is a health hazard, low concentrations, typically in the range of parts per million (ppm), need to be detected.

Different analytical techniques such as optical spectroscopy, mass spectrometry, gas chromatography, electro-chemical analysis, etc., may be used for detection of substances present in relatively low concentrations. One particular technique, optical spectrophotometry, is based on the absorption of electromagnetic radiation by the sample in a selected spectral range and is generally recognized to have relatively high sensitivity and speed of analysis. A spectrophotometric system typically has (i) a light source; (ii) a monochromator, which filters the light from the light source so that only a limited wavelength range is allowed to irradiate the gas sample contained in a sample cell; and (iii) a photo-detector, which measures the amount of light transmitted through the sample. Representative prior-art spectrophotometric systems operating in either ultraviolet (UV) or infrared (IR) parts of the spectrum are described, for example, in U.S. Patent Nos. 5,936,250 and 6,344,648, the teachings of both of which are incorporated herein by reference. However, one problem with prior-art spectrophotometric systems is that they are relatively difficult to adapt for portable, particularly hand-held, applications.

SUMMARY OF THE INVENTION

Problems in the prior art are addressed, in accordance with the principles of the present invention, by a portable spectrophotometric system for detecting one or more target substances. In a representative embodiment, a system of the invention has an optical grating, an array of photo-detectors, and a MEMS device having a movable plate positioned between the grating and the array.

Light transmitted through a gaseous sample is dispersed by the grating and is imaged onto the movable plate, which has a plurality of openings corresponding to selected absorption lines of the target substance. A small-amplitude oscillation is imparted onto the plate such that the openings periodically move in and out of alignment with the corresponding intensity features in the image, which modulates electrical signals generated by the corresponding photo-detectors. A lock-in signal processor analyzes the modulation pattern by comparing it to the pattern expected in the presence of the target substance. When a positive correlation between the patterns is established, the system warns the user about the presence of the target substance.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a schematic diagram of a spectrophotometric system according to one embodiment of the present invention;

Fig. 2 graphically shows optical absorption for mean latitude summer air at pressure p = 1 atm. and temperature T = 296 K;

Figs. 3A-B compare absorption spectra of air and hydrogen cyanide at p = 0.1 atm. and T = 296 K; and

Fig. 4 shows a top view of a MEMS device that can be used in the system of Fig. 1 according to one embodiment of the present invention.

DETAILED DESCRIPTION

Reference herein to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the invention. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments.

Fig. 1 shows a schematic diagram of a spectrophotometric system **100** according to one embodiment of the present invention. A beam of light generated by a broadband light source **102** is directed through a cell **104** containing a sample to be analyzed. Light transmitted through cell **104** is dispersed in wavelength by a grating **106** and is imaged by a cylindrical lens **108** onto a movable plate **110**. The image produced at the surface of plate **110** is a stripe of light, in which different locations along the length of the stripe correspond to different wavelengths. Plate **110** has a plurality of openings **112** and is preferably a part of a MEMS device **120**, which also includes a support structure **122** and one or more springs **124** connected between the support structure and the plate. Device **120** further includes an electrostatic actuator (not shown) adapted to controllably move plate **110** with respect to structure **122** as indicated by the double-headed arrow in Fig. 1. Plate **110** allows light to pass through openings **112** and substantially blocks the light impinging

onto other portions of the plate. An array of photo-detectors **130** located behind plate **110** converts the transmitted light into electrical signals, which are then applied to a signal processor **140**.

As will be further illustrated below, IR absorption of gases is typically characterized by the presence of relatively narrow absorption lines, each of which usually corresponds to a particular rotational and/or vibrational mode of the gas molecule. Each of these absorption lines produces a corresponding intensity feature in the image at plate **110**. For example, a relatively strong absorption line will produce a corresponding black (i.e., having substantially no light) area at plate **110** while the areas adjacent to the black area will have a relatively high light intensity. Position of each opening **112** within plate **110** is chosen such that it can be aligned with the intensity feature corresponding to a selected absorption line of the target gas to be detected. It is also preferred that, for each target gas, plate **110** has two or more openings **112**. In addition, plate **110** may have one or more openings **112** corresponding to selected strong absorption lines of air, which may be used for calibration purposes as further detailed below.

In a representative configuration, system **100** operates as follows. First, device **120** is wavelength calibrated. During calibration, the actuator of device **120** is biased to align openings **112** corresponding to absorption lines of air with the appropriate intensity features (e.g., black areas) of the image at plate **110**. Proper alignment of plate **110** is achieved when the intensity profile measured by detectors **130** has the expected intensity pattern corresponding to air. Next, detection of a target gas is performed as follows. When the target gas is present in cell **104**, the intensity profile measured by detectors **130**, in addition to the air pattern, will also include an intensity pattern corresponding to the target gas. After calibration, openings **112** corresponding to the target gas are aligned with the corresponding intensity features (if present) in the image at plate **110** resulting from light absorption by the target gas. However, due to the unknown and possibly low concentration of the target gas, these intensity features may be relatively weak. To enable detection of weak absorption, the actuator in device **120** is configured to impart onto plate **110** a small-amplitude oscillation, e.g., in the kHz frequency range, about the equilibrium position set during the calibration. Due to the oscillation, each opening **112** corresponding to the target gas periodically moves in and out of alignment with the respective intensity feature, thereby changing in a periodic fashion the amount of light transmitted through the opening and therefore modulating the signal generated by the corresponding detector **130**.

Processor **140**, preferably using lock-in detection techniques, measures the appropriate ac components having a frequency corresponding to the oscillation frequency of plate **110** in the signals generated by detectors **130**. To discriminate against false positives, processor **140** is preferably configured to verify correlations expected between the signals generated by different detectors **130** corresponding to the same target gas. Such correlations may include (i) simultaneous

presence of the appropriate ac components and/or (ii) proper relative amplitudes of said components in accordance with relative magnitudes of the corresponding absorption lines in the absorption spectrum of the target gas. In addition, processor **140** may optionally be configured to determine the concentration of the target gas using the measured ac amplitudes.

Figs. 2 and 3 further illustrate the principle of operation of system **100** in a representative embodiment adapted for the detection of hydrogen cyanide (HCN), a highly toxic gas. More specifically, Fig. 2 graphically shows optical absorption for mean latitude summer air at pressure p = 1 atm. and temperature T = 296 K; and Figs. 3A-B compare absorption spectra of air and HCN at p = 0.1 atm. and T = 296 K; the abundance of HCN is 1 ppm. Each value of absorption (A) shown in Figs. 2 and 3 represents a relative amount of electromagnetic radiation that is absorbed in a gas column of length l and is expressed by the following equation:

$$A = 1 - \exp(-k_\lambda l) \qquad (1)$$

where k_λ is the absorption coefficient at wavelength λ.

Fig. 2 shows optical absorption for a column (l = 1 m) of air having the following composition: 77.393230% of nitrogen; 20.710864% of oxygen; 1.862987% of water; 0.032701% of carbon dioxide; 0.000168% of methane; 0.000032% of nitrous oxide; 0.000015% of carbon monoxide; and 0.000003% of ozone. As indicated by the data in Fig. 2, air has certain spectral "transparency" windows (i.e., spectral regions where absorption is relatively weak), which are located between strong absorption bands of individual air components. For example, one such transparency window is between 5700 and 6600 cm^{-1}. One or more spectral transparency windows may be used to detect optical absorption of target gases. Alternatively, one or more relatively narrow gaps (not discernible in Fig. 2) between absorption lines composing a selected strong absorption band may similarly be used to detect optical absorption of target gases.

Figs. 3A-B show optical absorption spectra of air and HCN, respectively, in the spectral range from 6480 to 6500 cm^{-1}, which is within the spectral transparency window indicated above. Referring now to Fig. 3A, in one embodiment, a spectral line **302** corresponding to water vapor is selected as a calibration feature. Accordingly, plate **110** (Fig. 1) has opening **112-cal** indicated in Fig. 3A by the two vertical lines near spectral line **302**. During calibration, plate **110** is positioned such that opening **112-cal** aligns with line **302** as shown in Fig. 3A. Additional openings **112-cal** not shown in Fig. 3A may be used to achieve and/or verify the alignment.

Referring to Fig. 3B, a spectral line **304** corresponding to HCN is selected as a signature feature of that gas. Accordingly, plate **110** (Fig. 1) has opening **112-hc** indicated in Fig. 3B by the two vertical lines near spectral line **304**. When opening **112-cal** is aligned with line **302** as shown in Fig. 3A, opening **112-hc** aligns with line **304** as shown in Fig. 3B. The horizontal double-headed arrow in Fig. 3B indicates a representative oscillation amplitude for plate **110** (Fig. 1). Due to this

oscillation, the signal generated by detector **130** located behind opening **112-hc** is modulated with the frequency twice the oscillation frequency. Processor **140** (Fig. 1) processes the modulated signal, measures its amplitude, and preferably verifies that this modulated signal properly correlates with other modulated signals corresponding to additional openings **112-hc** (not shown in Fig. 3B). When a positive correlation is established, system **100** warns the user about the presence of HCN and optionally uses the modulation amplitudes to determine and display its concentration.

In a preferred embodiment, cell **104** is a multi-pass cell having an effective optical path length of about 1 to 10 m. A representative multi-pass cell that may be used in one embodiment of system **100** is described in U.S. Patent No. 5,173,749, the teachings of which are incorporated herein by reference. In one embodiment, cell **104** is an airtight cell, which has valves connected to a pump (not shown in Fig. 1) configured to reduce pressure in the cell prior to or after sample injection. Optionally, cell **104** has heaters to vaporize liquid samples. In another embodiment, cell **104** has vents enabling unencumbered gas exchange with ambient air.

Fig. 4 shows a top view of a MEMS device **420** that can be used as MEMS device **120** according to one embodiment of the present invention. Device **420** comprises a movable plate **410** supported on a wafer **422** by four serpentine springs **424a-d**. In different embodiments, a different number of springs may be used. Wafer **422** preferably comprises at least three layers: a substrate layer (not shown), an overlayer **402**, and a thin insulating layer (not shown) located between the substrate layer and the overlayer. The insulating layer electrically isolates overlayer **402** from the substrate layer. Overlayer **402** and the substrate layer may be silicon and the insulating layer may be silicon oxide. Plate **410** is formed using overlayer **402** while the underlying portions of the substrate and insulating layers are removed to enable the plate mobility. Plate **410** has six slots **412a-f**, two of which may be calibration slots corresponding to selected absorption lines of air and the remaining four slots may be slots corresponding to absorption lines of one or more target gases.

Device **420** further comprises a comb-drive actuator **406** including (i) a mobile portion **406a** connected to plate **410** and (ii) an immobile portion **406b** attached to wafer **422**. Portion **406a** of actuator **406** is formed using layer **402** and is detached from the underlying substrate and insulating layers to permit in-plane motion of that portion and plate **410**. Portion **406b** of actuator **406** is electrically connected to a contact pad **408** using a contact track **404**. Portion **406b** of actuator **406**, track **404**, and pad **408** are electrically isolated from the rest of the device structure using the underlying insulation of the insulating layer and the surrounding grooves in overlayer **402**. In contrast, portion **406a** of actuator **406** is in electrical contact with overlayer **402**, e.g., via springs **424c-d**. Thus, a voltage differential can be applied between portions **406a-b** of actuator **406**. In one configuration, layer **402** may be connected to a negative terminal of a voltage source (e.g., ground), whereas pad **408** may be connected to a positive terminal of that voltage source configured

to apply voltage between portions **406a-b** of actuator **406**. Contact pad **408** may be metal-plated as known in the art for better ohmic contact with a wire lead (not shown).

In one configuration, device **420** may be operated as follows. First, a suitable dc voltage is applied between portions **406a-b** of actuator **406**, e.g., as explained above, to align calibration slots **412** with the appropriate absorption lines of air. Spring force generated by deformed springs **424** counterbalances the attractive electrostatic force generated between portions **406a-b** of actuator **406**. Then, in addition to the dc voltage, a small ac voltage, for example, having a frequency of about 20 kHz, is applied between portions **406a-b**. The ac voltage causes plate **410** to oscillate at that frequency about the position corresponding to the dc voltage. Assuming that grating **106** has 1100 grooves per mm and lens **108** has a focal lens of about 50 mm, an ac voltage producing the oscillation amplitude of about 10 μm will effectively move slots **412** in and out of alignment with the corresponding absorption features of the image at plate **410**.

Device **420** may be fabricated from a silicon-on-insulator (SOI wafer) using different fabrication techniques. For example, an etch fabrication method may be used. It is known that silicon etches significantly faster than silicon oxide using, e.g., reactive ion etching (RIE). Similarly, silicon oxide etches significantly faster than silicon using, e.g., fluorine-based etchants. Relatively deep cavities in a relatively thick substrate layer may be defined using a standard, anisotropic etching technique, such as deep RIE. Deep RIE stops automatically at the oxide layer acting as an etch stop. Various parts of device **420** may be mapped onto the corresponding layer using lithography. Additional description of various etching steps may be found, for example, in U.S. Patent Nos. 6,201,631, 5,629,790 and 5,501,893, the teachings of all of which are incorporated herein by reference.

Although fabrication of device **420** has been described in the context of using silicon/silicon oxide SOI wafers, other suitable materials may similarly be used. The materials may be appropriately doped as known in the art. Various surfaces may be modified, e.g., by metal deposition and/or by ion implantation. Also, differently shaped plates, actuators, and/or support structures may be implemented without departing from the scope and principle of the invention. Different embodiments may include differently shaped and/or configured springs, where the term "spring" refers in general to any suitable elastic structure that can recover its original shape after being distorted.

Advantageously, due to the relatively small size of MEMS device **420**, a spectrophotometric system of the invention employing said device has a size suitable for portable applications. Further miniaturization may be achieved by implementing the signal processor (e.g., processor **140)** and the array of photo-detectors (e.g., detectors **130)** in a single integrated circuit. In addition, processor

140, detectors **130**, and MEMS device **120** (or device **420**) may be implemented as a system on a chip (SOC).

While this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Although the invention was described in reference to IR light, it may also be practiced using UV light or other parts of the electromagnetic spectrum. System **100** may be designed to use spectral features other than absorption lines, e.g., an edge of a relatively wide absorption band or an emission line. For example, in one embodiment, light source **102** is a laser adapted to excite fluorescence in the sample contained in cell **104** and openings **112** correspond to selected fluorescence lines of the sample. Openings **112** may correspond to two or more target substances. Various modifications of the described embodiments, as well as other embodiments of the invention, which are apparent to persons skilled in the art to which the invention pertains are deemed to lie within the principle and scope of the invention as expressed in the following claims.

Although the steps in the following method claims, if any, are recited in a particular sequence with corresponding labeling, unless the claim recitations otherwise imply a particular sequence for implementing some or all of those steps, those steps are not necessarily intended to be limited to being implemented in that particular sequence.